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Impact of urban albedo on microclimate

Computational investigation in London

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ABSTRACT: The urban albedo (UA), defined as the ratio of the reflected to the incoming shortwave radiation at the upper edge of urban canyons, quantifies their ability to reflect solar radiation towards the sky. This research investigates the impact of real-world urban geometries and optical properties of facades and roads materials on the UA and street level microclimate in London. The Indexed Sphere (IVS) algorithm of ENVI-met 4.4.4 is used to compute the UA of several canyon configurations. The accuracy of the IVS algorithm is evaluated against measurements on a 1:10 physical model reproducing the geometry and materials of the case study area. The simulation results show that reflective materials applied to the canyon surfaces are more effective in increasing the UA of canyons with low aspect ratios. The use of reflective materials in urban canyons always increases the amount of reflections at the street level, increasing the mean radiant temperature in most cases. Air temperature is not affected by the canyon's façades reflectivity while it shows a significant daytime reduction for increased roads' reflectivity. The results provide preliminary guidelines for the control of UA and the improvement of microclimate in London.

KEYWORDS: Urban Albedo, reflective materials, Heat island, microclimate, ENVImet

1. INTRODUCTION

The increase of absorption of solar radiation and heat storage by urban structures are significant contributing factors to the urban heat island (UHI) intensity in cities [1] [2]. The UHI, although more pronounced in high radiation and high ambient temperature cities, has negative impacts on thermal comfort, health and building energy use also in cities of high latitudes such as London (Lat 51.5 N) [3], [4]. For this reason, tacking urban warming and overheating risk is one of the priorities of the city's climate change adaptation strategy [5].

There exist two major strategies for UHI mitigation, based on two physical principles: (1) decreasing solar absorption in the urban environment and (2) increasing evapotranspiration using greenery and water. The first strategy is based on the use of reflective urban surfaces, which reduce solar absorption and surface temperature and, consequently, air temperature [1], [6].

In the urban context, the cooling potential of reflective materials can be decreased due to the interaction of solar radiation with urban geometry [7]–[9]. The concept of "Urban Albedo" (UA) was thus developed to bring together the effect of urban geometry and materials' optical properties on the overall ability of urban areas to reflect short-wave radiation toward the sky. The UA is defined as the ratio of the outgoing to the incoming shortwave radiation at the upper edge of the urban canopy layer [10]. The variability of UA in urban areas has been investigated using experimental models [11], [12] and numerical models [10], [13], [14]. These studies agree that, for a given site coverage ratio, the UA decreases for an increase of façade density, average building height and building height variability. This is explained by the increase of multiple reflections and radiation trapping within vertical surfaces. In fact, simulation studies have also shown that the urban textures with higher density of vertical surfaces have higher UHI intensity [15]. The limitation of these studies on UA is that urban areas are always simplified to symmetric canyon geometries or equal size squared footprint buildings on orthogonal grids with uniform material cover for roads, walls and roofs.

Some studies also highlighted that using reflective materials in the urban context may worsen the outdoor thermal conditions due to the increase of reflections and mean radiant temperature at the street level [16], [17].

For these reasons, the correlation between the reflection coefficients of roads' and facades' materials and the canyon UA is not straightforward, as well as the impact of UA on the street level microclimate.

This study investigates the impact of real-world urban geometries and optical properties of facades and roads materials on UA and microclimate in a residential area of London. This is intended to provide guidelines for the control of UA to improve outdoor thermal comfort in London.

2. MATERIALS AND METHODS

This research is based on microclimate simulations with ENVImet V4.4.4 and measurements on a physical model of the studied urban area. The experimental and computational data are used to achieve the following objectives:

1) Evaluate the performance of the new ENVImet IVS algorithm for radiation transfer
2) Assess the net impact of different spatial distributions of reflective materials on the UA of canyons with different geometries
3) Understand the net impact of UA change on the street level thermal environment

2.1 Physical model

A 1:10 physical model of the real urban area was built at the University of Kent (Canterbury, UK). The physical model accurately reproduces the geometry and material distribution of the real urban area (Figure 1). The model is located outdoors and equipped with pairs of pyranometers – one looking upward and the other looking downward - to measure the incoming and reflected radiation in three points: in the middle of the model at the equivalent height of 10m above the tallest building (Point 1) and at the eaves level in two urban canyons (Point 2 and 3).

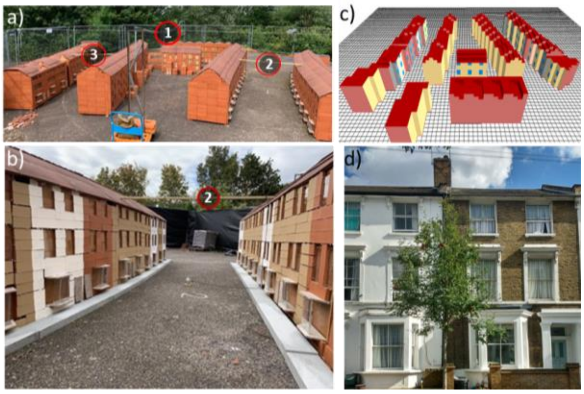

Figure 1: a) physical model and location of the pyranometers 1, 2 and 3; b) detail of the physical model materials; c) ENVImet model for the IVS algorithm evaluation; d) Detail of the facades of the case study area

Table 1: Model's materials specification

Materials	Reflection coefficient
Asphalt	0.11
Roof tiles	0.21
Concrete paving	0.27
Red Bricks	0.31
Buff lime painted Bricks	0.42
Magnolia painted Bricks	0.52
White painted Bricks	0.78

2.2 Evaluation of the ENVImet IVS algorithm

An ENVImet model reproducing the geometry and materials of the physical model (Figure 1) was used to assess the model's accuracy in the calculation of solar radiation reflections within urban canyons.

To this aim, the forcing global solar radiation was adjusted based on the incoming solar radiation measured on top of the physical model and the simulation output "Reflected short-wave radiation from the lower hemisphere" was compared to the reflected solar radiation measured on the physical model. The comparison was performed for the three construction phased reported in table 2, using the reflection coefficients of table 1, so as to compare ENVImet' sensitivity to material change.

Table 2: Physical model construction phases

Model phases	Materials
1- As Built	tiles, red bricks and glass
2- With Paving	Concrete paving was added
3- Façade Colours	Façade colour were added and paving removed

All ENVImet simulations were run using the Indexed Sphere (IVS) algorithm of ENVI-met 4.4.4. The IVS algorithm calculates the reflected shortwave radiation and emitted longwave radiation from any element (walls, roofs, ground surface and vegetation) proportional to the view factor of those elements and considering the actual state of the element (i.e. surface temperature and solar irradiation). This method is thus much more accurate than the simplified method which calculates uniform reflections within urban canyons based on the average albedo of the materials.

2.2 ENVImet model for UA and microclimate investigations

The physical model has some limitations such as the absence of vegetation and a limited number of buildings compared to the real urban area. Therefore, a more complete ENVImet model of the case study area was built to provide realistic boundary conditions to assess the impact of material change on UA and microclimate (Figure 2). The ENVImet model has vegetation, covers a larger portion of the urban area and is forced with local air temperatures measured on site [18].

A number of scenarios with reflective materials applied to the roads and the facades of the case study area were simulated to assess the impact on the canyons UA and on the street level microclimate. The microclimate impact was assessed in terms of air temperature and mean radiant temperature change at the pedestrian level. The tested scenarios for material distribution are reported in table 3. These were tested on two canyon geometries: low-rise canyons with aspect ratio of about 0.75 and high-rise canyons with aspect ratio of about 1.5. The low-rise canyons correspond to the aspect ratio of the canyons in the case study area. The high-rise configuration was obtained keeping the same building footprint of the case study area and doubling the height of the buildings. The results of these 8 combinations of geometry and reflective material distribution have been analysed for the canyons 1, 2 and 3 highlighted in figure 2, which have also different orientation.

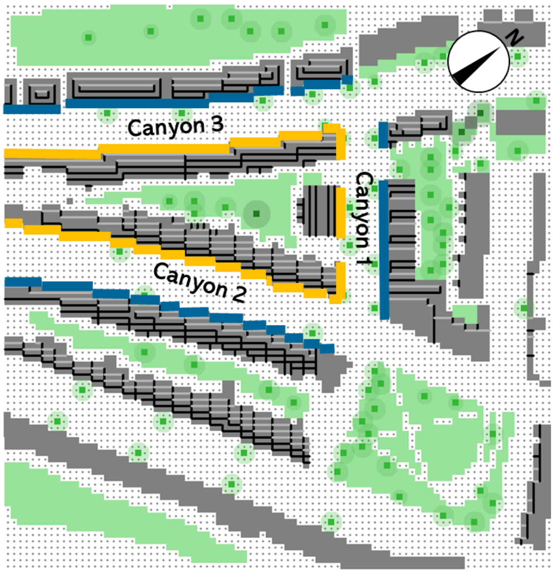

Figure 2: Plan of the ENVImet model used to test the impact of reflective materials on the canyons' UA and the microclimate at street level.

Table 3: Simulated scenarios to assess the impact of reflective materials applied to different canyons' surfaces

Model ID	Reflection Coeff.	Distribution of reflective material
A1 out	r=0.6	Reflective material applied to the **outer marked facades** (Fig 2)
A1 centre	r=0.6	Reflective material applied to the **inner marked facades** (Fig 2)
A1 top	r=0.6	Reflective material applied to the **top half of the canyons' facades**
A2	r=0.5	Reflective material applied to the **roads**

3. RESULTS AND DISCUSSION

3.1. Performance of the ENVImet IVS algorithm

The comparison between the reflected radiation measured at the physical model and computed by ENVImet is shown in Figure 3. The comparison shows that ENVImet slightly underestimates the reflections of solar radiation at the eaves level of urban canyons while it overestimates the reflections on top of the model from noon and until sunset. Therefore, ENVImet tends to overestimate the UA of urban canyons in the afternoon compared to the measurements. In spite of these discrepancies, the overall performance of the IVS algorithm is in good agreement with the measurements in terms of daily UA. The daily UA is calculated as the ratio of the total reflected radiation to the total incoming radiation over the reference day. On top of the model, the daily UA measured and calculated was 0.12 and 0.15 respectively. At the eaves level, the measured and calculated UA was 0.09 - 0.1 and 0.07 respectively.

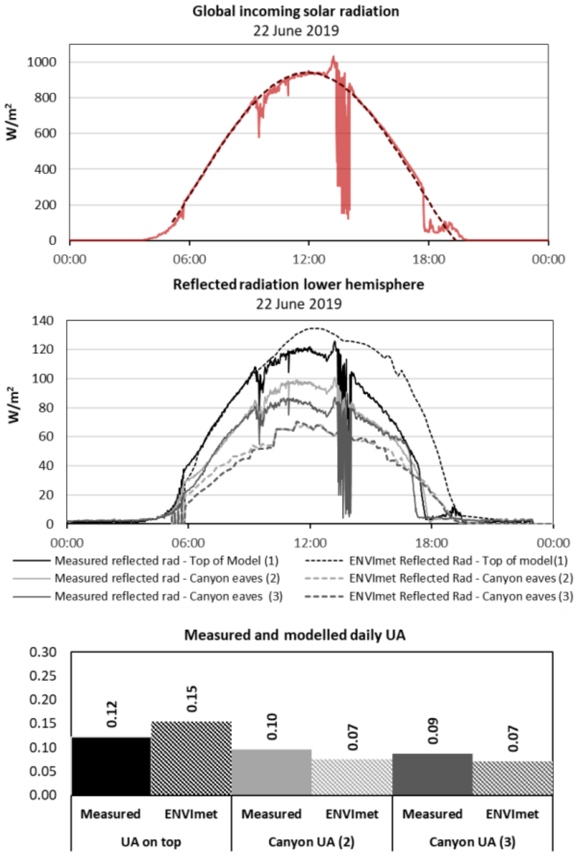

Figure 3: Comparison of measured and simulated incoming global solar radiation (graph on top), reflected solar radiation (graph in the middle) and daily urban albedo

Table 1: Sensitivity of the ENVImet IVS algorithm to material change on roads and facades in the computation of canyon reflections compared to measurements

	Measured		***ENVImet***	
Model ID and Ref Day	Canyon UA (2)	ΔUA	Canyon UA (2)	ΔUA
As built 23/07/2019	**0.100**	-	**0.077**	-
Paving 20/09/19	**0.123**	23%	**0.105**	37%
Facade colours 06/10/19	**0.156**	56%	**0.114**	48%

The comparison shown in figure 3 correspond to the construction phase named "As built" (table 2). The impact of road and façade materials on the canyon UA as measured and computed by ENVImet is reported in table 4. The results show that ENVImet captures the increase of UA due to materials change, even if the percentage of UA change is slightly different compared to those measured on the physical model. This can be also due to the unavoidable geometry differences between the physical model and the ENVImet model due to the orthogonal mesh constraints.

3.2 Impact of reflective materials on UA for different canyon aspect ratios

The results of the simulations testing the impact of reflective materials on the canyons' UA for different aspect ratios, are reported in figure 4. The canyon daily albedo has been calculated as the ratio of the total reflected to the total incoming short-wave radiation in the three canyon sections presented in figure 4. For each canyon, the hourly incoming and reflected radiation was computed as the mean value of all the cells of the section (cell size 2x2 m) and the daily sum of the mean reflected and incoming radiation was used to calculate the daily UA of the three canyons.

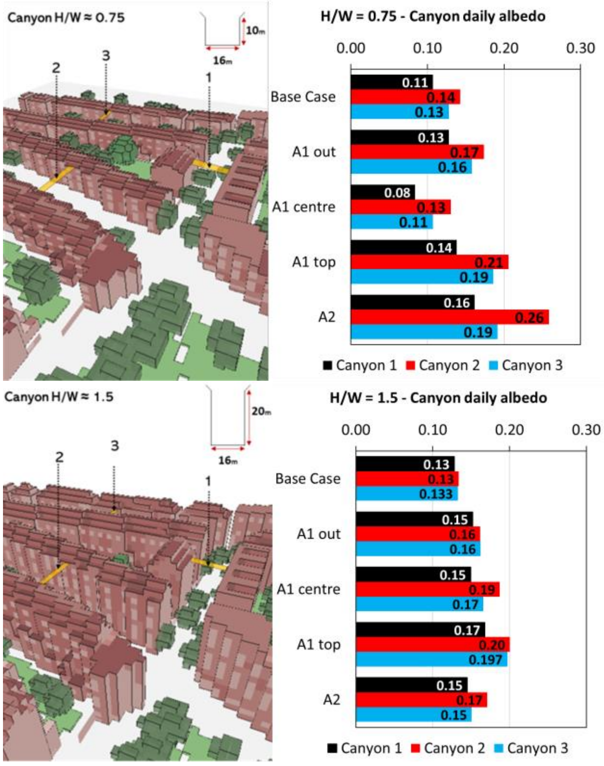

Figure 4: Impact of the reflective material scenarios on the three canyons' daily urban albedo

The simulation results show some interesting differences on the impact of reflective materials in different canyon geometries. The reflective materials have a larger impact on low-rise aspect ratio canyons compared to high-rise ones. This is particularly evident for the scenario A2 – reflective roads – which determines a much higher relative increase of UA in the canyons with aspect ratio of 0.75 compared to the ones with aspect ratio 1.5. However, when the reflective materials are applied to the top half of the canyon's facades (A1 TOP), the two canyon geometries show a similar relative and absolute variation of the UA. This might be explained by the fact that the top half of the canyon facades receive a similar amount of solar radiation despite the different geometry. The results presented in figure 4 indicate that the two canyon geometries have less variation of the UA for the base case materials compared to variations for other cases examined. However, this similarity does not result to the same microclimate at the street level, because the increase of building height determines a significant reduction of the solar radiation reaching the street level in the high-rise urban area.

The results also indicate that the highest relative increase of UA is achieved with scenario A2 in the low-rise canyons and with the scenario A1 TOP in the high-rise canyons. Some differences exist in the UA of the three different canyons due to their orientation. Canyon 2 shows the highest variations of UA with the use of reflective materials since it is the canyon receiving the highest amount of solar radiation among the three analysed.

3.3 Impact of UA on microclimate

The microclimate impact of the tested scenarios has been analysed in terms of air temperature and mean radiant temperature change at the street level (1.5 m high) compared to the base case material distribution. The thermal environment of the base case configurations is reported in figure 5 for the two canyon aspect ratios.

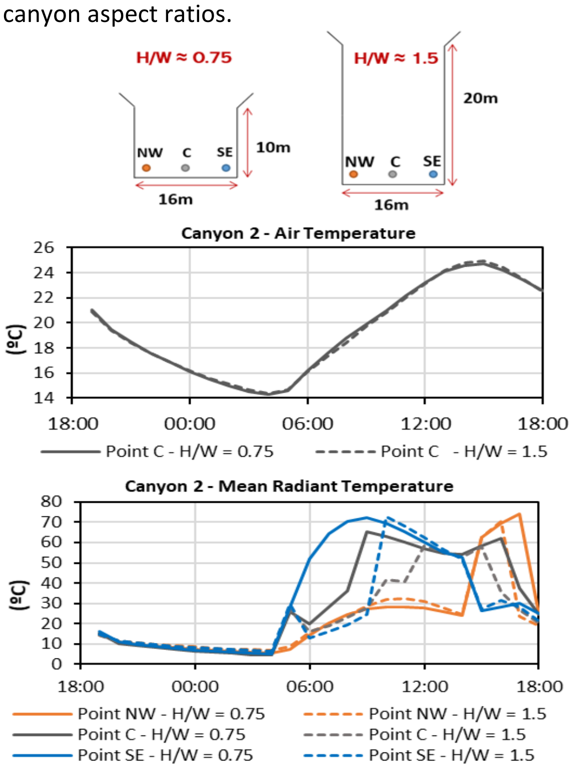

Figure 5: Air temperature and mean radiant temperature in different points of the two canyons configurations with the base case material distribution. NW and SE indicate the orientation of the adjacent façade.

The comparison presented in figure 5 highlights that the increase of building height determines a significant decrease of mean radiant temperature in the morning and the afternoon, due to the reduction of solar radiation reaching the street level. Conversely, the two canyon geometries with the base case material distribution have the same air temperature; this is due to the fact that the simulations were forced with the same air temperatures, measured in the case study area. In reality, a change in the canyon aspect ratio would probably determine variations in the daytime and night-time air temperatures; however this is not the aim of this study and the base case air temperature should be interpreted just as a term of comparison for the tested scenarios.

The most representative results of the microclimate impact of the tested scenarios are reported in Figure 6. The graphs refer to the street level thermal environment of the canyon 2 (Figure 2), which showed the maximum change in UA for the tested reflective materials scenarios.

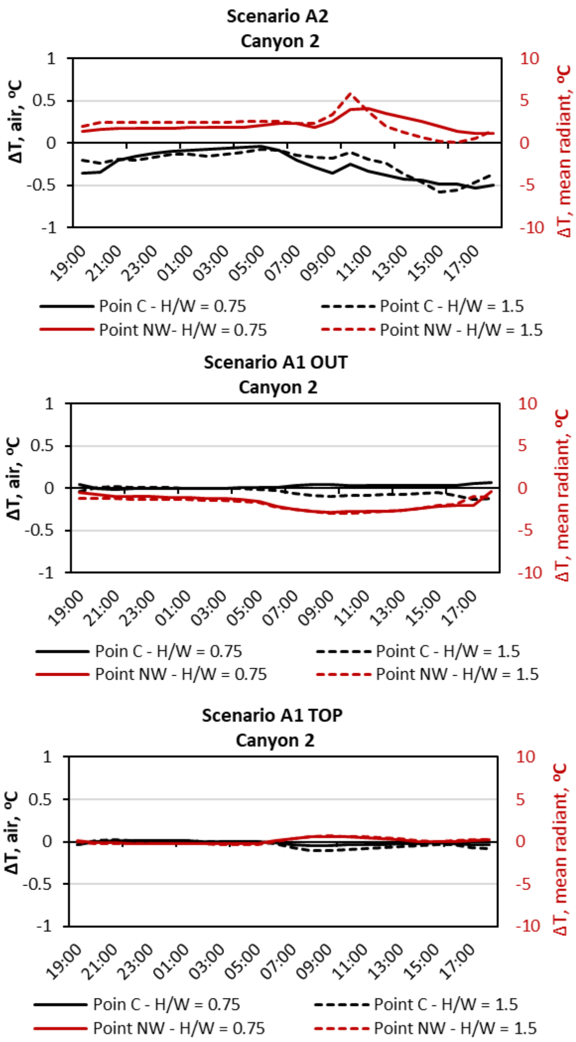

Figure 6: ENVImet results of the impact of reflective materials on roads (A2) and facades (A1 OUT and A1 TOP) on the air temperature and mean radiant temperature change at the street level compared to the base case.

The graphs show that increasing the reflectivity of roads or facades has a different impact on air temperature and mean radiant temperature. This is due to the geometry of urban canyon surfaces that, in most cases, reflects solar radiation towards other urban surfaces instead to the sky. In fact, all the tested scenarios show an increase of reflections at the street level which determines an increase of the mean radiant temperature in most cases.

The first graph in figure 6 shows that increasing the road reflectivity results to an increase of mean radiant temperature but also a decrease of air temperature during daytime. Despite the different aspect ratios, the relative difference is similar in high-rise and low-rise urban canyons. This result can be explained by the fact that a higher reflection coefficient of the road material allows a reduction of the surface temperature during daytime, with a positive impact on air temperature. However, it also results to an increase of the reflected solar radiation received by the building facades, resulting to an increase of the mean radiant temperature. Similar results have been reported by previous studies carried out at lower latitudes locations [16], [17].

The impact of increased façade reflectivity on air temperature is negligible in all the scenarios analysed. Similarly, the impact of increased façade reflectivity on the mean radiant temperature is smaller compared to the one determined by the increase of roads' reflectivity. In some cases, increasing the reflectivity of facades also allows to reduce the mean radiant temperature, as shown in figure 6 for the scenario A1 OUT. However, this does not happen in all the canyons analysed and seems to depend on the facades' orientation. The use of reflective materials on the top half of the canyon façade has almost no impact on air temperature nor mean radiant temperature at the street level. This scenario also allowed a significant increase of the canyons' UA.

The microclimate results presented in this study do not allow to draw any conclusion on the net impact of the use of reflective materials on outdoor thermal comfort in London, because of the contrasting impacts on mean radiant temperature, reflections and air temperature at the street level. A further elaboration of the microclimate outputs into comprehensive indices such as the Physiological Equivalent Temperature (PET) is needed to compare the performance of the different scenarios on the outdoor thermal comfort. For a comprehensive analysis, the impact of the reflective material scenarios on UA and outdoor thermal comfort needs to be investigated also in the winter seasons. These will be the next steps of this research.

4. CONCLUSION

This paper presented results from experimental and computational investigations on the impact of real-world urban geometries and optical properties of facades and roads materials on the urban albedo and the street level microclimate in a case-study area of London. The results provided insights on the real cooling potential of reflective materials in the urban context at London's latitude. Different scenarios involving the use of reflective materials on roads and facades were tested on low-rise and high-rise urban canyon configurations.

The results indicate that increasing the reflectivity of roads has the highest impact on the increase of urban albedo in low-rise urban canyon configurations. Instead, in canyon with higher aspect ratio, increasing the reflectivity of the top half of the canyon' facades allows the highest increase of urban albedo.

In terms of microclimate, the daytime air temperature shows a reduction for an increase of the road reflectivity while it is not affected by the facades' reflectivity. All the scenarios determine an increase of reflections at the street level which reduces or erases the positive impact of surface temperature reduction on the mean radiant temperature. Instead, the use of reflective materials only on the top half of the canyon façades does not affect the street level microclimate. Therefore, it can be concluded that this could be an effective strategy to increase UA and potentially mitigate the UHI intensity at the urban scale without compromising the street level microclimate.

The study also provided a novel evaluation of ENVImet IVS algorithm for detailed radiation transfer calculation. The comparison with measurements showed a good agreement and confirmed its suitability for investigations on the impact of reflective materials on urban albedo and microclimate in urban canyons.

These results provide novel insights into the interrelationships between urban form, material properties and urban microclimate in high latitude locations. Further developments will be aimed at developping design guidelines for the control of UA and the improvement of the outdoor thermal environment in London and cities of similar latitudes.

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